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Title: Calibration of a Gamma Calibration Well with an Energy-Compensated Geiger-Mueller (G-M) Tube

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Abstract

A working-standard Radcal model 1515 radiation monitor with the 1800cc ion chamber was used previously at Los Alamos National Laboratory (LANL) to calibrate and perform routine QA checks on the low-level gamma well, which produces exposure rates in the range of 0.2 mR/h to 10 mR/h. During long integration times (e.g. 24-48 hrs) with the 1800 cc ion chamber, which were required to obtain the necessary precision, changes in temperature and pressure and fluctuations in the zero offset introduced errors that were difficult to account for. An energy compensated G-M tube (SHP-270) was calibrated as a Working Standard to calibrate and perform QA checks on the low-level gamma well. Energy correction factors were determined since the SHP-270 does not have a linear energy response. Monte Carlo N-Particle (MCNP) code was used to determine the exposure rate in 50 keV energy bins as a function of source distance in the well. The results of these calculations were folded into the energy correction factors of the SHP-270 to determine the *Corrected Exposure Rate* as a function of source distance. To recalibrate the gamma well, the *Corrected Exposure Rates* were loaded into the source control algorithm, which was then verified to work correctly.

Introduction

A working-standard Radcal model 1515 radiation monitor with the appropriate ion chamber has been used previously to calibrate and perform routine QA checks on four Cs-137 gamma wells that are used to calibrate Health Physics (HP) instruments at the Los Alamos National Laboratory (LANL). The four gamma wells produce a range of exposure rates from 0.2 mR/h to 500 R/h. For the low-level gamma well, which produces exposure rates in the range of 0.2 mR/h to 10 mR/h, long integration times (e.g. 24 – 48 hours) using the 1800cc chamber were required to obtain the necessary precision. Changes in pressure and temperature during these long integration times made it difficult to determine the appropriate pressure and temperature correction factors. Also, the zero offset on the model 1515 radiation monitor when it was used with the 1800cc chamber was found to drift from –0.03 mR/h to 0.19 mR/h when sampled over a 24-hour time period, thereby adding to the uncertainty of the measurements. See attachment 1 for the results of the zero offset measurement.

An energy-compensated G-M tube was selected to calibrate and perform routine QA checks on the low-level gamma well since it is not affected by pressure and temperature changes and integration times of less than one hour meet the precision requirement for the measurement. The G-M tube was calibrated in a tertiary free-in-air field with a Cs-137 source. The energy response of the G-M tube was characterized with an X-ray range and Cs-137 source and energy correction factors were determined in energy bins of 50 keV. The low-level gamma well was modeled in detail employing MCNP-4C[1] to determine the exposure rate contribution in 50 keV energy bins as a function of source distance. The energy response of the G-M tube was folded into the MCNP results to

[1] J.F. Briesmeister, Ed., "MCNP™. A General Monte Carlo N-Particle Transport Code," Version 4C, Los Alamos National Laboratory Report LA-13709-M Manual (March 2000).

obtain correction factors for the G-M tube as a function of source distance in the well. These correction factors were applied to exposure rate results obtained with the G-M tube as a function of source distance to determine the actual exposure rate of the well for calibration purposes. Calibrating the low-level gamma well using the energy-compensated G-M tube resulted in a more precise and accurate calibration in less time compared to the model 1515 radiation monitor with the 1800 cc ion chamber.

Free-in-Air Calibration of the SHP-270

The calibration constant (CC) for the SHP-270 was determined free-in-air at the 2.5 mr/h exposure rate point from the tertiary standard free-in-air field. Data at this CC point was collected for 300 seconds with the SHP-270 in scaler mode to allow a minimum of 10000 counts to be observed to limit statistical errors (i.e. < 1% error). Once the CC was determined, additional exposure rate points were obtained and averaged to verify the calibration and linearity of the SHP-270. Table 1 illustrates the results of calibrating the SHP-270 free-in-air.

Table 1: Calibration Results of SHP-270 Free-in-Air

Free-In-Air Exposure Rate (mr/h)	Time (sec)	Count 1 (mr/h)	Count 2 (mr/h)	Count 3 (mr/h)	Average (mr/h)	Normalized Response
0.2	600	0.201	0.209	0.198	0.203	1.013
0.4	300	0.413	0.422	0.408	0.414	1.036
0.5	300	0.493	0.513	0.505	0.504	1.007
1.0	300	1.003	1.009	.994	1.002	1.002
2.5	300	2.49	2.51	2.48	2.49	0.997
4.0	300	3.99	3.97	4.02	3.993	0.998

Table 1 illustrates that the SHP-270 responds fairly linearly over the exposure range checked with one outlier at the 0.4 mr/h point (i.e. 3.6%). Since this outlier represents the worse case error associated with any of the calibration points obtained, it was assumed this outlier is 3σ (3.6%) away from the normalized response. Therefore, the error associated with calibrating the SHP-270 is 1.2% (1σ). The error associated with the free-in-air field from the Cs-137 sources themselves has been analyzed previously by Olsher[2] to be 0.92% (1σ). Therefore, the total error associated with calibrating the SHP-270 free-in-air with the Cs-137 sources is 1.5% (1σ).

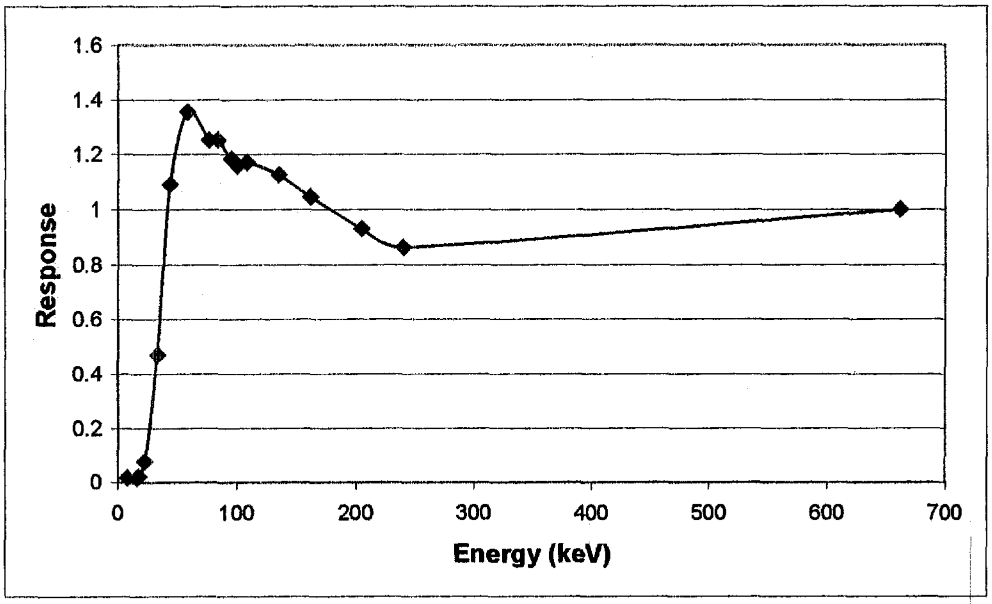
Energy Correction Factors

Even though the SHP-270 is an energy compensated GM-tube, it does not have a linear energy response when compared to ion chambers. Figure 1 is a graph of the SHP-270 response as a function of energy. The energy response of the SHP-270 was characterized on ESH-4's X-Ray Range using both fluorescent x-ray and heavily-filtered direct beam

[2] R.H. Olsher, "Error Analysis for the Reference Radiation Fields at the SM-130 Irradiation and Evaluation Facility" (Memo ESH-4-RIC-96-039).

techniques. Fluorescent techniques are produced on a series of secondary targets and span the energy range from 8 keV to 100 keV, while filtered direct beam techniques produce spectra centered at 108, 135, 162, 205, and 240 keV. The high-energy response was measured in a Cs-137 field. The response of the SHP-270 probe was normalized to Cs-137.

Figure 1: Normalized Response vs. Energy



An energy correction factor was determined for the SHP-270 by calculating the energy response normalized to Cs-137 in energy bins of 50 keV. For the majority of energy bins, linear interpolation was used to determine the response for that bin. For the 0–50 keV, 50-100 keV and 100-150 keV bins, the response was determined by fitting the data with an equation since more that two points were available. After fitting the data, the value obtained at the midpoint for the 50-100 keV and 100-150 keV bins, i.e. 75 keV and 125 keV, were used to calculate the response respectively. For the 0-50 keV bin, a value of 34.7 keV was used since this is the midpoint of the data fit, i.e. 16 keV to 58.8 keV. The R^2 value of the fit data was at least for 0.99 for all three bins. Table 2 shows the SHP-270 energy response and correction factor for each bin.

Table 2: SHP-270 Energy Response Correction Factors

Energy Bin (keV)	Energy Response	Correction Factor
50	0.856	1.168
100	1.215	0.823
150	1.200	0.834
200	0.944	1.059
250	0.865	1.156
300	0.882	1.134
350	0.898	1.114
400	0.914	1.094
450	0.931	1.074
500	0.947	1.056
550	0.963	1.038
600	0.980	1.021
650	0.996	1.004
662	1	1

Calibration of Low Level Gamma Well with the SHP-270

The low level gamma well was calibrated with a three-step process. The first step was to measure the exposure rate over the well as a function of index number (i.e. distance). Again, the SHP-270 was placed in scaler mode and the count time was set so that at least 10000 counts were observed to limit statistical errors (i.e. < 1% error). Table 3 illustrates the results of these measurements.

Table 3: Exposure Rate Measurements vs. Index Number

Index Number	Distance (cm)	Time (min)	mr/h
150	349.47	50	0.171
300	332.34	40	0.187
600	298.08	40	0.232
900	263.82	30	0.294
1200	229.56	25	0.387
1350	212.43	20	0.455
1500	195.3	15	0.541
1650	178.17	15	0.651
1800	161.04	10	0.799
1950	143.91	10	1.01
2100	126.78	10	1.305
2250	109.65	10	1.769
2400	92.52	10	2.440
2550	75.39	10	3.640
2700	58.26	10	5.740
2850	41.13	10	10.360

The second step was to determine the exposure rate energy contribution at the top of the Well in 50 keV energy bins (e.g. 0-50 keV, 50-100 keV, . . . 650-700 keV) as a function of index number. This step was necessary to fold in the energy response of the SHP-270. This was accomplished by using MCNP-4C to model the Well at each of the Index numbers illustrated in Table 3. Figure 2 is an illustration of the model.

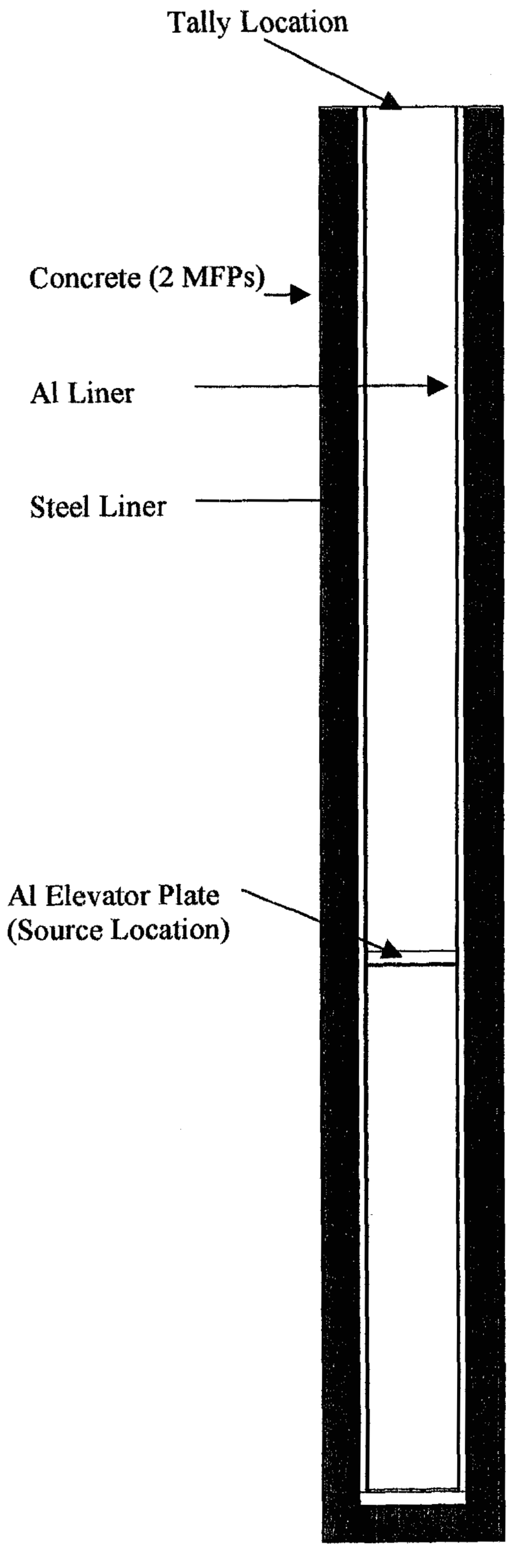


Figure 2: Sketch of MCNP Model

Attachment 2 contains the results of this effort. The column labeled *"Contribution (mr/h)"* are results from MCNP and the column labeled *"Corrected Contribution(mr/h)"* are results from MCNP with the energy response correction factors of the SHP-270 folded in. From these two columns, a correction factor can be determined at each index number. After reviewing attachment 2, it is interesting to note that higher correction factors are applied when the sources are closer to the top of the gamma well. To determine the cause of this behavior, the MCNP model was modified to determine the contribution at the tally location directly from the source, i.e. the scatter contribution from the well walls (e.g. Al, steel and concrete) was not included.

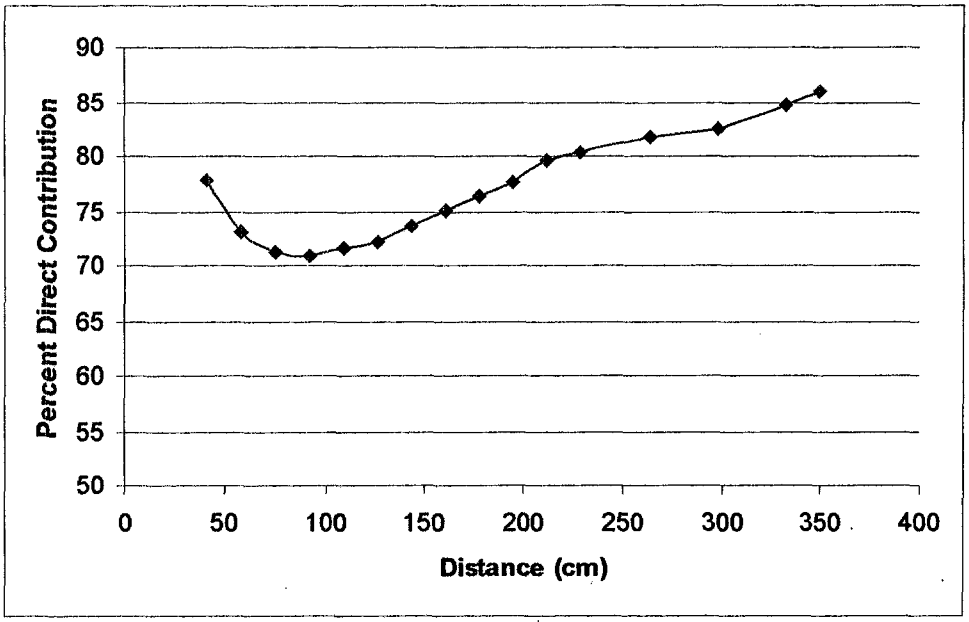


Figure 3: Percent Contribution from the Direct Component vs. Distance

As shown from Figure 3, the contribution from the direct component to the tally location is greatest when the source is located at the bottom of the well. As the source is raised from the bottom of the well, the contribution from the direct component decreases and the contribution from the scatter component increases. One potential explanation for this behavior is that photons contributing to the tally location will undergo more scatter events the deeper the source is located in the well. Since the photon undergoes more scattering events as a function of increasing distance in the well, the higher the probability a photon will undergo a photoelectric interaction, and thus not contribute to the tally location. At approximately 100-cm in the well, the greatest contribution from the scatter component to the tally location takes place. At distances closer than 100-cm, the contribution from the direct component again increases. This behavior is most likely due to the significantly increasing solid angle between the source and the to the top of the well at such short distances.

The exposure rate results from MCNP were compared to the SHP-270 measured exposure rate results with the energy correction factors applied. This comparison was made to validate the MCNP model used to determine the correction factors. Table 4 made to validate the MCNP model used to determine the correction factors. Table 4 illustrates the results of this comparison. (Note: the results from MCNP were adjusted for distance using $1/r^2$ methodology since the SHP-270 measurements are taken at 2.5-inches above the well. Figure 4 illustrates, the exposure rate does fall off $1/r^2$).

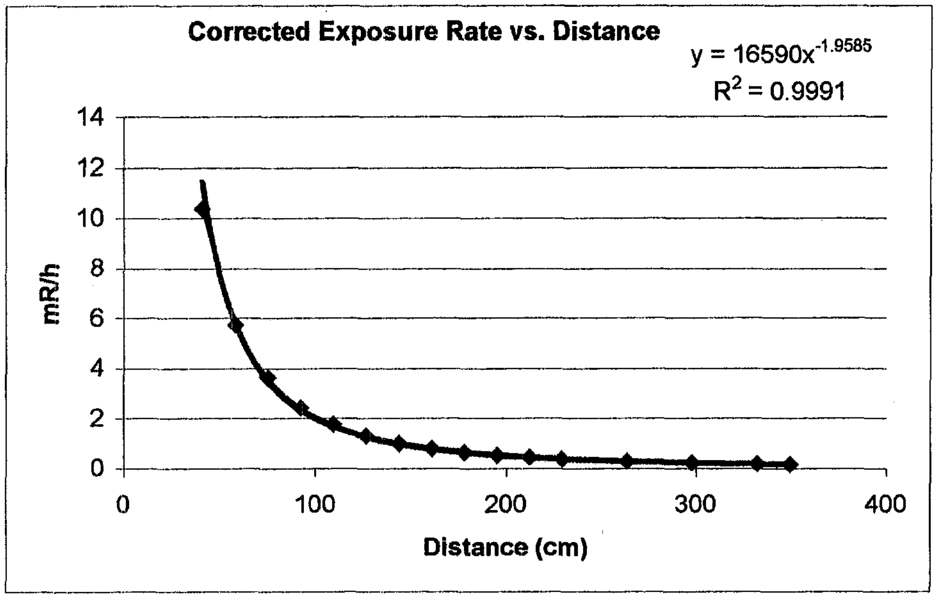


Figure 4: Exposure Rate vs. Distance

Table 4: Comparison of MCNP Calculations with Measured Exposure Rates

Index Number	Distance (cm)	MCNP (mr/h)	MCNP Distance Corrected (mr/h)	Measured Results with Correction Factor (mr/h)	% Change From Measured Result
150	349.47	0.161	0.156	0.172	-9.75
300	332.34	0.179	0.172	0.189	-8.63
600	298.08	0.230	0.220	0.234	-5.87
900	263.82	0.304	0.290	0.297	-2.44
1200	229.56	0.412	0.390	0.391	-0.15
1350	212.43	0.486	0.458	0.460	-0.36
1500	195.3	0.586	0.550	0.547	0.41
1650	178.17	0.708	0.660	0.660	0.12
1800	161.04	0.899	0.832	0.810	2.64
1950	143.91	1.147	1.052	1.025	2.64
2100	126.78	1.509	1.368	1.326	3.17
2250	109.65	2.048	1.830	1.799	1.72
2400	92.52	2.925	2.561	2.485	3.07
2550	75.39	4.458	3.792	3.713	2.15
2700	58.26	7.337	5.966	5.857	1.85
2850	41.13	14.072	10.560	10.558	0.01

As illustrated from Table 4, the results obtained from MCNP agree favorably to the measured results with the energy response correction factor applied.

The third and final step employed in calibrating Well 8 was to load in the energy corrected exposure rates as a function of the index number into the source control algorithm. Table 5 lists this data.

Table 5: Data Loaded into Source Control Algorithm

Index No.	Measured Exp. Rate (mr/h)	Correction Factor	Corrected Exp. Rate (mr/h)
150	0.171	1.008	0.172
300	0.187	1.009	0.189
600	0.232	1.010	0.234
900	0.294	1.010	0.297
1200	0.387	1.011	0.391
1350	0.455	1.011	0.460
1500	0.541	1.012	0.547
1650	0.651	1.013	0.660
1800	0.799	1.014	0.810
1950	1.01	1.015	1.025
2100	1.305	1.016	1.326
2250	1.769	1.017	1.799
2400	2.44	1.018	2.485
2550	3.64	1.020	3.713
2700	5.74	1.020	5.857
2850	10.36	1.019	10.558

The data was fit with a 5th order polynomial and had R^2 value of 0.996. Equation 1 represents the fit data, i.e. exposure rate as a function of index number.

$$y=1.42E\text{-}15x^5 - 8.96E\text{-}12x^4 + 2E\text{-}8x^3 - 2.09E\text{-}5x^2 + 0.0086x - 0.8293 \qquad \text{Eqn. 1}$$

After the data was logged into the source control algorithm, various exposure rates were selected using the algorithm and the associated exposure rate measured with the SHP-270 to ensure the algorithm fitted the data correctly. The SHP-270 was placed in scaler mode and the time set so that at least 5000 counts were observed during the count period to limit statistical errors (i.e. 2%). Table 6 illustrates the results of this verification.

Table 6: Verification of Source Control Algorithm Fit

Selected Exposure Rate (mr/h)	Index Number	Count Time (seconds)	Measured Exposure Rate	Percent Change from Selected Exposure Rate
0.2	377	1260	0.200	0
0.4	1223	625	0.398	-0.5
0.5	1426	500	0.489	-2.2
0.8	1789	350	0.789	-1.375
1.0	1936	250	1.007	0.7
1.5	2167	200	1.492	-0.533
2.0	2306	200	1.971	-1.450
2.5	2403	200	2.42	-3.2
4.0	2577	200	4.00	0
5.0	2649	200	4.86	-2.8
6.0	2704	200	5.79	-3.5
8.0	2783	200	7.74	-3.25
10.0	2839	200	9.81	-1.9

As illustrated from Table 6 above, the algorithm fit the data correctly. To determine the error associated with the algorithm fitting the data, the worse error associated with the fit (i.e. 3.5%) was assumed to be 3σ away from the conventionally true value (CTV). Propagating the error throughout this analysis, the total error associated with calibrating Well 8 is 1.9% (1σ).

Conclusions

Calibrating the low-level gamma well the SHP-270 resulted in a more accurate and precise calibration compared to that of the Radcal Model 1515 with the 1800 cc ion chamber since various factors that could affect the calibration were removed during the calibration process. These factors included long integration times; pressure and temperature changes and the zero offset fluctuating over –0.03 to 0.19 mR/h.

Attachment 1

	1 hr	2 hr	3 hr	4 hr	5 hr	6 hr	7 hr	8 hr	9 hr	10 hr	11 hr	12 hr
	0.03	0	0.03	0.01	0.03	0.01	0	0.01	-0.01	0.03	0	0.01
	0.04	0.06	0.01	0.03	0.01	0.04	0.01	0.02	0.02	0	-0.01	0
	0	0.04	0.01	0	0	0	-0.01	0	0.01	0	0.01	0
	0.01	0.01	0.01	0.02	0.01	0.01	0.06	0.01	0.02	0.08	0	0.06
	0.03	0	0.03	0.01	-0.01	0.12	0.02	0.01	0	0.03	0.03	0.02
	0.03	0.02	0.1	0.19	-0.02	0.01	0	0.03	0	0	0.01	0
	0.03	0	0	0.01	0.01	0.02	0	0.02	0.02	0.01	0.12	0.07
	0.03	0.02	0.05	0.04	0.04	0.01	0.06	0.01	0.16	0.04	0	0.03
	0.11	0.02	0.04	0.08	0.06	0	0	0.04	0.01	0	0.03	0
	0.03	0.03	0.01	0.16	0.01	-0.01	0	0.01	0.08	0	0.05	0.01
	0.01	0.02	0	0	0.01	0.08	0.07	0.11	0	0	0.06	0
	0.03	0.01	0.03	0.01	0.01	0.02	0	0	0.02	0	0.01	0
AVG	0.032	0.019	0.027	0.047	0.013	0.026	0.018	0.023	0.028	0.016	0.026	0.017
STD	0.027	0.018	0.028	0.064	0.021	0.038	0.029	0.030	0.048	0.025	0.037	0.025

	13 hr	14 hr	15 hr	16 hr	17 hr	18 hr	19 hr	20 hr	21 hr	22 hr	23 hr	24 hr
	0.03	0.01	0.02	0	0.08	-0.01	0.06	0	0	0	0.05	0
	0.01	0.03	0.01	-0.01	0	0.01	0.08	-0.01	0.04	0.02	-0.01	0
	-0.01	0.01	0.01	0.01	0.08	0	0.04	0.01	-0.01	0	-0.01	0
	0.02	0.02	0.01	0.02	0	0.01	-0.02	0.01	-0.03	-0.01	0	0
	0.01	0.01	0.02	0	0.01	0.02	-0.01	0.01	-0.03	0.08	-0.01	0
	0.02	0	0.02	0.02	0.11	0.01	0.03	-0.01	-0.01	0	-0.02	-0.01
	0.06	0.01	0.01	0.01	0.03	0.02	0.02	0.04	0.08	-0.01	0	0.07
	0.06	0.01	0.02	0.01	0.01	-0.01	0.01	-0.01	0	-0.03	0	0.03
	0.04	0.17	0.01	0.02	0.01	0.03	0.04	0	0	0	0.01	0
	0	0.03	0.01	0.08	0.01	0	-0.03	0.01	0.01	-0.01	0.01	-0.01
	0.04	0.03	0.03	0.01	0	0	0	0	-0.03	0.01	-0.01	0.01
	0.03	0.02	0.02	0.01	0	0.05	0	0	-0.01	-0.02	0	-0.01
AVG	0.026	0.029	0.016	0.015	0.028	0.011	0.018	0.004	0.001	0.003	0.001	0.007
STD	0.022	0.045	0.007	0.022	0.039	0.017	0.033	0.014	0.032	0.028	0.018	0.023

AVG (all)	0.019	**Min**	-0.03
STD (all)	0.032	**Max**	0.19

Attachment 2

Index 150		
Energy (MeV)	Contribution (mr/hr)	Corrected Contribution (mr/hr)
5.00E-02	5.18E-05	6.05E-05
1.00E-01	2.07E-04	1.70E-04
1.50E-01	7.70E-04	6.42E-04
2.00E-01	1.84E-03	1.95E-03
2.50E-01	2.27E-03	2.62E-03
3.00E-01	1.46E-03	1.65E-03
3.50E-01	1.86E-03	2.07E-03
4.00E-01	1.76E-03	1.93E-03
4.50E-01	2.09E-03	2.24E-03
5.00E-01	2.38E-03	2.51E-03
5.50E-01	2.86E-03	2.97E-03
6.00E-01	3.67E-03	3.75E-03
6.50E-01	7.25E-03	7.28E-03
7.00E-01	1.33E-01	1.33E-01
Total	1.61E-01	1.63E-01
	Correction Factor	1.009

Index 300		
Energy (MeV)	Contribution (mr/hr)	Corrected Contribution (mr/hr)
5.00E-02	3.58E-05	4.18E-05
1.00E-01	2.37E-04	1.95E-04
1.50E-01	8.71E-04	7.26E-04
2.00E-01	1.97E-03	2.09E-03
2.50E-01	2.67E-03	3.09E-03
3.00E-01	1.77E-03	2.01E-03
3.50E-01	2.03E-03	2.26E-03
4.00E-01	2.30E-03	2.51E-03
4.50E-01	2.64E-03	2.84E-03
5.00E-01	3.15E-03	3.33E-03
5.50E-01	3.23E-03	3.35E-03
6.00E-01	4.43E-03	4.52E-03
6.50E-01	8.67E-03	8.70E-03
7.00E-01	1.45E-01	1.45E-01
Total	1.79E-01	1.81E-01
	Correction Factor	1.009

Index 600		
Energy (MeV)	Contribution (mr/hr)	Corrected Contribution (mr/hr)
5.00E-02	4.42E-05	5.16E-05
1.00E-01	3.77E-04	3.10E-04
1.50E-01	1.36E-03	1.13E-03
2.00E-01	2.84E-03	3.01E-03
2.50E-01	3.01E-03	3.47E-03
3.00E-01	2.41E-03	2.73E-03
3.50E-01	3.28E-03	3.66E-03
4.00E-01	3.08E-03	3.37E-03
4.50E-01	3.83E-03	4.12E-03
5.00E-01	4.30E-03	4.54E-03
5.50E-01	4.60E-03	4.77E-03
6.00E-01	6.33E-03	6.46E-03
6.50E-01	1.22E-02	1.22E-02
7.00E-01	1.82E-01	1.82E-01
Total	2.30E-01	2.32E-01
	Correction Factor	1.010

Index 900		
Energy (MeV)	Contribution (mr/hr)	Corrected Contribution (mr/hr)
5.00E-02	4.40E-05	5.14E-05
1.00E-01	5.22E-04	4.30E-04
1.50E-01	1.88E-03	1.57E-03
2.00E-01	3.77E-03	3.99E-03
2.50E-01	4.20E-03	4.85E-03
3.00E-01	4.04E-03	4.58E-03
3.50E-01	3.71E-03	4.13E-03
4.00E-01	3.92E-03	4.29E-03
4.50E-01	5.36E-03	5.76E-03
5.00E-01	4.97E-03	5.25E-03
5.50E-01	6.72E-03	6.98E-03
6.00E-01	9.57E-03	9.77E-03
6.50E-01	1.84E-02	1.84E-02
7.00E-01	2.37E-01	2.37E-01
Total	3.04E-01	3.07E-01
	Correction Factor	1.010

Index 1200		
Energy (MeV)	Contribution (mr/hr)	Corrected Contribution (mr/hr)
5.00E-02	1.62E-04	1.89E-04
1.00E-01	1.07E-03	8.78E-04
1.50E-01	3.36E-03	2.80E-03
2.00E-01	5.06E-03	5.36E-03
2.50E-01	7.32E-03	8.46E-03
3.00E-01	5.61E-03	6.37E-03
3.50E-01	4.98E-03	5.54E-03
4.00E-01	6.43E-03	7.04E-03
4.50E-01	8.41E-03	9.03E-03
5.00E-01	7.95E-03	8.39E-03
5.50E-01	9.18E-03	9.52E-03
6.00E-01	1.35E-02	1.37E-02
6.50E-01	2.44E-02	2.45E-02
7.00E-01	3.15E-01	3.15E-01
Total	4.12E-01	4.17E-01
	Correction Factor	1.011

Index 1350		
Energy (MeV)	Contribution (mr/hr)	Corrected Contribution (mr/hr)
5.00E-02	4.39E-05	5.12E-05
1.00E-01	1.31E-03	1.08E-03
1.50E-01	3.75E-03	3.13E-03
2.00E-01	6.34E-03	6.71E-03
2.50E-01	7.71E-03	8.91E-03
3.00E-01	6.63E-03	7.52E-03
3.50E-01	7.86E-03	8.76E-03
4.00E-01	7.74E-03	8.46E-03
4.50E-01	9.40E-03	1.01E-02
5.00E-01	1.02E-02	1.07E-02
5.50E-01	1.21E-02	1.26E-02
6.00E-01	1.70E-02	1.74E-02
6.50E-01	2.89E-02	2.90E-02
7.00E-01	3.67E-01	3.67E-01
Total	4.86E-01	4.92E-01
	Correction Factor	1.011

Index 1500		
Energy (MeV)	Contribution (mr/hr)	Corrected Contribution (mr/hr)
5.00E-02	1.10E-04	1.28E-04
1.00E-01	1.58E-03	1.30E-03
1.50E-01	4.74E-03	3.95E-03
2.00E-01	8.05E-03	8.52E-03
2.50E-01	1.07E-02	1.23E-02
3.00E-01	7.76E-03	8.81E-03
3.50E-01	1.04E-02	1.16E-02
4.00E-01	1.07E-02	1.17E-02
4.50E-01	1.25E-02	1.34E-02
5.00E-01	1.38E-02	1.45E-02
5.50E-01	1.70E-02	1.77E-02
6.00E-01	2.38E-02	2.43E-02
6.50E-01	3.42E-02	3.43E-02
7.00E-01	4.31E-01	4.31E-01
Total	5.86E-01	5.93E-01
	Correction Factor	1.012

Index 1650		
Energy (MeV)	Contribution (mr/hr)	Corrected Contribution (mr/hr)
5.00E-02	1.86E-04	2.18E-04
1.00E-01	1.95E-03	1.61E-03
1.50E-01	6.54E-03	5.45E-03
2.00E-01	1.08E-02	1.14E-02
2.50E-01	1.28E-02	1.47E-02
3.00E-01	1.07E-02	1.21E-02
3.50E-01	1.19E-02	1.32E-02
4.00E-01	1.38E-02	1.51E-02
4.50E-01	1.56E-02	1.67E-02
5.00E-01	1.71E-02	1.80E-02
5.50E-01	2.12E-02	2.20E-02
6.00E-01	3.52E-02	3.59E-02
6.50E-01	3.86E-02	3.88E-02
7.00E-01	5.12E-01	5.12E-01
Total	7.08E-01	7.17E-01
	Correction Factor	1.013

Attachment 2

Index 1800

Energy (MeV)	Contribution (mr/hr)	Corrected Contribution (mr/hr)
5.00E-02	1.58E-04	1.84E-04
1.00E-01	2.92E-03	2.40E-03
1.50E-01	9.11E-03	7.59E-03
2.00E-01	1.44E-02	1.53E-02
2.50E-01	1.69E-02	1.95E-02
3.00E-01	1.45E-02	1.64E-02
3.50E-01	1.81E-02	2.02E-02
4.00E-01	1.78E-02	1.94E-02
4.50E-01	2.20E-02	2.36E-02
5.00E-01	2.43E-02	2.57E-02
5.50E-01	2.94E-02	3.06E-02
6.00E-01	5.24E-02	5.34E-02
6.50E-01	4.05E-02	4.06E-02
7.00E-01	6.36E-01	6.36E-01
Total	8.99E-01	9.11E-01
Correction Factor		1.014

Index 1950

Energy (MeV)	Contribution (mr/hr)	Corrected Contribution (mr/hr)
5.00E-02	2.47E-04	2.88E-04
1.00E-01	4.17E-03	3.43E-03
1.50E-01	1.31E-02	1.09E-02
2.00E-01	2.10E-02	2.22E-02
2.50E-01	2.30E-02	2.66E-02
3.00E-01	2.06E-02	2.33E-02
3.50E-01	2.43E-02	2.71E-02
4.00E-01	2.65E-02	2.90E-02
4.50E-01	2.71E-02	2.92E-02
5.00E-01	3.22E-02	3.40E-02
5.50E-01	4.56E-02	4.74E-02
6.00E-01	6.89E-02	7.03E-02
6.50E-01	4.30E-02	4.32E-02
7.00E-01	7.97E-01	7.97E-01
Total	1.15E+00	1.16E+00
Correction Factor		1.015

Index 2100

Energy (MeV)	Contribution (mr/hr)	Corrected Contribution (mr/hr)
5.00E-02	3.18E-04	3.72E-04
1.00E-01	6.20E-03	5.10E-03
1.50E-01	1.93E-02	1.61E-02
2.00E-01	2.94E-02	3.12E-02
2.50E-01	3.28E-02	3.79E-02
3.00E-01	3.01E-02	3.41E-02
3.50E-01	3.38E-02	3.77E-02
4.00E-01	3.33E-02	3.64E-02
4.50E-01	4.08E-02	4.39E-02
5.00E-01	4.83E-02	5.10E-02
5.50E-01	7.32E-02	7.60E-02
6.00E-01	8.87E-02	9.05E-02
6.50E-01	4.26E-02	4.28E-02
7.00E-01	1.03E+00	1.03E+00
Total	1.51E+00	1.53E+00
Correction Factor		1.016

Index 2250

Energy (MeV)	Contribution (mr/hr)	Corrected Contribution (mr/hr)
5.00E-02	5.14E-04	6.01E-04
1.00E-01	8.83E-03	7.26E-03
1.50E-01	2.82E-02	2.35E-02
2.00E-01	4.20E-02	4.45E-02
2.50E-01	4.69E-02	5.41E-02
3.00E-01	4.18E-02	4.74E-02
3.50E-01	4.65E-02	5.18E-02
4.00E-01	5.26E-02	5.76E-02
4.50E-01	5.82E-02	6.26E-02
5.00E-01	7.93E-02	8.37E-02
5.50E-01	1.12E-01	1.16E-01
6.00E-01	9.92E-02	1.01E-01
6.50E-01	4.22E-02	4.24E-02
7.00E-01	1.39E+00	1.39E+00
Total	2.05E+00	2.08E+00
Correction Factor		1.017

Index 2400

Energy (MeV)	Contribution (mR/h)	Corrected Contribution (mR/h)
5.00E-02	6.14E-04	7.17E-04
1.00E-01	1.43E-02	1.18E-02
1.50E-01	4.75E-02	3.96E-02
2.00E-01	6.54E-02	6.93E-02
2.50E-01	7.46E-02	8.62E-02
3.00E-01	6.87E-02	7.79E-02
3.50E-01	7.43E-02	8.28E-02
4.00E-01	8.49E-02	9.29E-02
4.50E-01	1.04E-01	1.12E-01
5.00E-01	1.41E-01	1.49E-01
5.50E-01	1.47E-01	1.53E-01
6.00E-01	1.02E-01	1.05E-01
6.50E-01	3.73E-02	3.75E-02
7.00E-01	1.96E+00	1.96E+00
Total	2.92E+00	2.98E+00
Correction Factor		1.018

Index 2550

Energy (MeV)	Contribution (mr/hr)	Corrected Contribution (mr/hr)
5.00E-02	1.10E-03	1.28E-03
1.00E-01	2.32E-02	1.91E-02
1.50E-01	7.97E-02	6.64E-02
2.00E-01	1.15E-01	1.22E-01
2.50E-01	1.19E-01	1.38E-01
3.00E-01	1.14E-01	1.29E-01
3.50E-01	1.33E-01	1.49E-01
4.00E-01	1.59E-01	1.74E-01
4.50E-01	2.08E-01	2.23E-01
5.00E-01	2.15E-01	2.27E-01
5.50E-01	1.61E-01	1.67E-01
6.00E-01	9.63E-02	9.83E-02
6.50E-01	3.53E-02	3.54E-02
7.00E-01	3.00E+00	3.00E+00
Total	4.46E+00	4.55E+00
Correction Factor		1.020

Index 2700

Energy (MeV)	Contribution (mR/h)	Corrected Contribution (mR/h)
5.00E-02	1.02E-03	1.19E-03
1.00E-01	4.22E-02	3.48E-02
1.50E-01	1.46E-01	1.22E-01
2.00E-01	2.03E-01	2.15E-01
2.50E-01	2.09E-01	2.42E-01
3.00E-01	2.20E-01	2.50E-01
3.50E-01	2.82E-01	3.14E-01
4.00E-01	3.36E-01	3.68E-01
4.50E-01	3.11E-01	3.34E-01
5.00E-01	2.41E-01	2.55E-01
5.50E-01	1.49E-01	1.55E-01
6.00E-01	8.37E-02	8.54E-02
6.50E-01	3.73E-02	3.74E-02
7.00E-01	5.07E+00	5.07E+00
Total	7.34E+00	7.49E+00
Correction Factor		1.020

Index 2850

Energy (MeV)	Contribution (mr/hr)	Corrected Contribution (mr/hr)
5.00E-02	1.96E-03	2.29E-03
1.00E-01	7.27E-02	5.98E-02
1.50E-01	2.99E-01	2.50E-01
2.00E-01	4.28E-01	4.53E-01
2.50E-01	4.58E-01	5.29E-01
3.00E-01	6.23E-01	7.06E-01
3.50E-01	6.01E-01	6.69E-01
4.00E-01	4.61E-01	5.04E-01
4.50E-01	3.06E-01	3.29E-01
5.00E-01	2.04E-01	2.16E-01
5.50E-01	1.26E-01	1.30E-01
6.00E-01	8.15E-02	8.32E-02
6.50E-01	6.40E-02	6.42E-02
7.00E-01	1.03E+01	1.03E+01
Total	1.41E+01	1.43E+01
Correction Factor		1.019

Calibration of a Gamma Calibration Well with an Energy-Compensated Geiger-Mueller (G-M) Tube

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Abstract

A working-standard Radcal model 1515 radiation monitor with the 1800cc ion chamber was used previously at Los Alamos National Laboratory (LANL) to calibrate and perform routine QA checks on the low-level gamma well, which produces exposure rates in the range of 0.2 mR/h to 10 mR/h. During long integration times (e.g. 24-48 hrs) with the 1800cc ion chamber, which were required to obtain the necessary precision, changes in temperature and pressure and fluctuations in the zero-offset introduced errors that were difficult to account for. An energy compensated G-M tube (SHP-270) was calibrated as a Working Standard to calibrate and perform QA checks on the low-level gamma well. Energy correction factors were determined since the SHP-270 does not have a linear energy response. Monte Carlo N-Particle (MCNP) code was used to determine the exposure rate in 50 keV energy bins as a function of source distance in the well. The results of these calculations were folded into the energy correction factors of the SHP-270 to determine the *Corrected Exposure Rate* as a function of source distance. To recalibrate the gamma well, the *Corrected Exposure Rates* were loaded into the source control algorithm, which was then verified to work correctly.

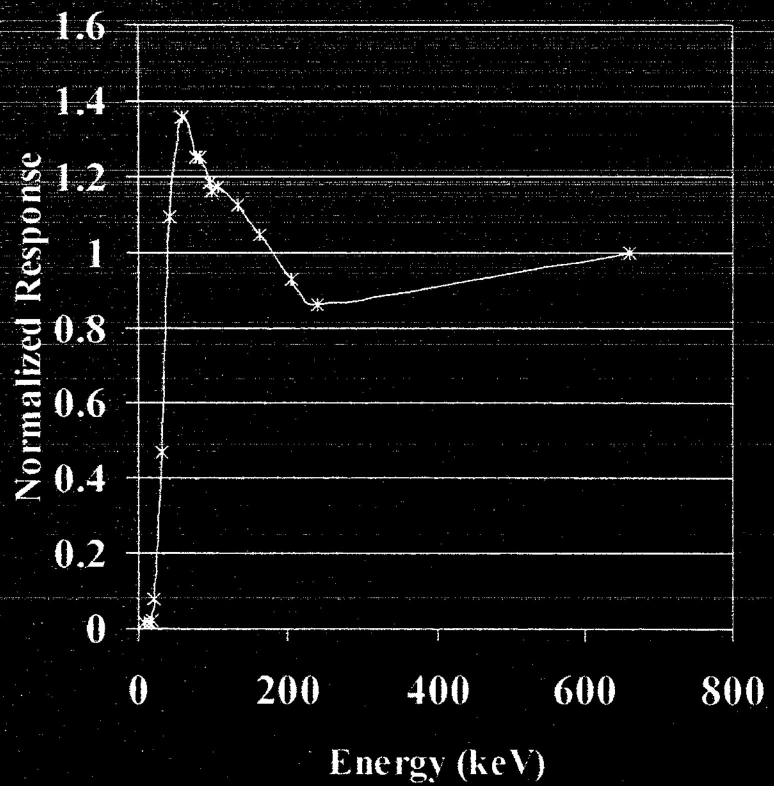
Calibration of the SHP-270 Probe

- Calibrated in a Tertiary Free-In-Air Cs-137 Field
- Calibration Constant (CC) determined at 2.5 mR/h
- Data Collected to Limit Counting Statistics to < 1% (i.e. >10000 counts collected)
- Total Error Associated with Calibration Propagated to be 1.5% (1σ)

Results of Calibrating the SHP-270 Free-in-Air

Free-In-Air Exposure Rate (mR/h)	Time (sec)	Count 1 (mR/h)	Count 2 (mR/h)	Count 3 (mR/h)	Average (mR/h)	Normalized Response
0.2	600	0.201	0.209	0.198	0.203	1.013
0.4	300	0.413	0.422	0.408	0.414	1.036
0.5	300	0.493	0.513	0.505	0.504	1.007
1.0	300	1.003	1.009	.994	1.002	1.002
2.5	300	2.49	2.51	2.48	2.49	0.997
4.0	300	3.99	3.97	4.02	3.993	0.998

Energy Response of SHP-270



- Characterized with X-Ray Range and Cs-137 Source
- Fluorescent Techniques (8 keV – 100 keV)
- Filtered Direct Beam Techniques (108, 135, 162, 205, and 240 keV)
- Response Normalized to Cs-137

Determination of Energy Correction Factors

- Energy Correction Factors Determined in Energy Bins of 50 keV
- Linear Interpolation Used with Bins having only 2 Data Points
- Bins Having > 2 points
  - Data fit with equations
  - R^2 at least 0.99

Energy Response Correction Factors

Energy Bin (keV)	Energy Response	Correction Factor
50	0.856	1.168
100	1.215	0.823
150	1.200	0.834
200	0.944	1.059
250	0.865	1.156
300	0.882	1.134
350	0.898	1.114
400	0.914	1.094
450	0.931	1.074
500	0.947	1.056
550	0.963	1.038
600	0.980	1.021
650	0.996	1.004
662	1	1

Calibration of Gamma Well with SHP-270

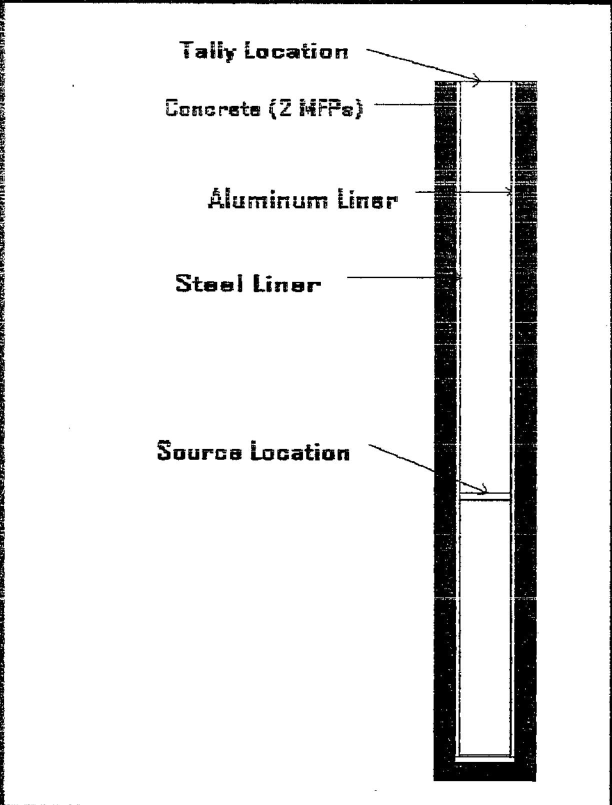
3 Step Process

1) Measure Well Exposure Rate as a Function of Index Number (i.e. distance)
2) Determine Exposure Rate Energy Contribution in 50 keV Energy Bins as a Function of Index Number (i.e. Correction Factors).
3) Load into Source Algorithm the Energy Corrected Exposure Rates as a Function of Index Number.

1st Step: Measure Well Exposure Rate as a Function of Index Number

Index Number	Distance (cm)	Time (min)	mR/h
150	349.47	50	0.171
300	332.34	40	0.187
600	298.08	40	0.232
900	263.82	30	0.294
1200	229.56	25	0.387
1350	212.43	20	0.455
1500	195.3	15	0.541
1650	178.17	15	0.651
1800	161.04	10	0.799
1950	143.91	10	1.01
2100	126.78	10	1.305
2250	109.65	10	1.769
2400	92.52	10	2.440
2550	75.39	10	3.640
2700	58.26	10	5.740
2850	41.13	10	10.360

2nd Step: Determine Exposure Rate Contribution in 50 keV Energy Bins



- Gamma Well Modeled in Detail with MCNP™-4C
  - Exposure Rate as a Function of Index Number Determined in 50 keV Energy Bins
  - Results Folded into Energy Response Correction Factors
  - Calibration Correction Factor Determined at Each Index Number (min=0.9% max=2%)
- MCNP Results Compared to Corrected Measured Results as a Verification MCNP Model

Example Correction Factors @ Index Numbers

index 150		
Energy (MeV)	Contribution (mr/hr)	Corrected Contribution (mr/hr)
5.00E-02	5.18E-05	6.05E-05
1.00E-01	2.07E-04	1.70E-04
1.50E-01	7.70E-04	6.42E-04
2.00E-01	1.84E-03	1.95E-03
2.50E-01	2.27E-03	2.62E-03
3.00E-01	1.46E-03	1.65E-03
3.50E-01	1.86E-03	2.07E-03
4.00E-01	1.76E-03	1.93E-03
4.50E-01	2.09E-03	2.24E-03
5.00E-01	2.38E-03	2.51E-03
5.50E-01	2.86E-03	2.97E-03
6.00E-01	3.67E-03	3.75E-03
6.50E-01	7.25E-03	7.28E-03
7.00E-01	1.33E-01	1.33E-01
Total	1.61E-01	1.63E-01
Correction Factor		1.009

index 1650		
Energy (MeV)	Contribution (mr/hr)	Corrected Contribution (mr/hr)
5.00E-02	1.86E-04	2.18E-04
1.00E-01	1.95E-03	1.61E-03
1.50E-01	6.54E-03	5.45E-03
2.00E-01	1.08E-02	1.14E-02
2.50E-01	1.28E-02	1.47E-02
3.00E-01	1.07E-02	1.21E-02
3.50E-01	1.19E-02	1.32E-02
4.00E-01	1.38E-02	1.51E-02
4.50E-01	1.56E-02	1.67E-02
5.00E-01	1.71E-02	1.80E-02
5.50E-01	2.12E-02	2.20E-02
6.00E-01	3.52E-02	3.59E-02
6.50E-01	3.86E-02	3.88E-02
7.00E-01	5.12E-01	5.12E-01
Total	7.08E-01	7.17E-01
Correction Factor		1.013

index 2850		
Energy (MeV)	Contribution (mr/hr)	Corrected Contribution (mr/hr)
5.00E-02	1.96E-03	2.29E-03
1.00E-01	7.27E-02	5.98E-02
1.50E-01	2.99E-01	2.50E-01
2.00E-01	4.28E-01	4.53E-01
2.50E-01	4.58E-01	5.29E-01
3.00E-01	6.23E-01	7.06E-01
3.50E-01	6.01E-01	6.69E-01
4.00E-01	4.61E-01	5.04E-01
4.50E-01	3.06E-01	3.29E-01
5.00E-01	2.04E-01	2.16E-01
5.50E-01	1.26E-01	1.30E-01
6.00E-01	8.15E-02	8.32E-02
6.50E-01	6.40E-02	6.42E-02
7.00E-01	1.03E+01	1.03E+01
Total	1.41E+01	1.43E+01
Correction Factor		1.019

Comparison of MCNP Calculations with Measured Exposure Rates

Index Number	Distance (cm)	MCNP Results (mR/h)	Measured Results with Correction Factors (mR/h)	% Change
150	349.47	0.156	0.172	-9.75
300	332.34	0.172	0.189	-8.63
600	298.08	0.220	0.234	-5.87
900	263.82	0.290	0.297	-2.44
1200	229.56	0.390	0.391	-0.15
1350	212.43	0.458	0.460	-0.36
1500	195.3	0.550	0.547	0.41
1650	178.17	0.660	0.660	0.12
1800	161.04	0.832	0.810	2.64
1950	143.91	1.052	1.025	2.64
2100	126.78	1.368	1.326	3.17
2250	109.65	1.830	1.799	1.72
2400	92.52	2.561	2.485	3.07
2550	75.39	3.792	3.713	2.15
2700	58.26	5.966	5.857	1.85
2850	41.13	10.560	10.558	0.01

3rd Step: Load Results Into Source Control Algorithm

- Measured Exposure Rates with Correction Factors Applied Loaded into Algorithm
- Data fit with a 5th Order Polynomial
  - $y=1.42E\text{-}15x^5 - 8.96E\text{-}12x^4 + 2E\text{-}8x^3 - 2.09E\text{-}5x^2 + 0.0086x - 0.8293$
  - R^2 value of fit data = 0.996
- Verification of Source Algorithm Fit
  - Exposure Rates Measured at Selected Points

Verification of Source Algorithm Fit

Selected Exposure Rate (mr/h)	Index Number	Measured Exposure Rate	% Change from Selected Exposure Rate
0.2	377	0.200	0
0.4	1223	0.398	-0.5
0.5	1426	0.489	-2.2
0.8	1789	0.789	-1.375
1.0	1936	1.007	0.7
1.5	2167	1.492	-0.533
2.0	2306	1.971	-1.450
2.5	2403	2.42	-3.2
4.0	2577	4.00	0
5.0	2649	4.86	-2.8
6.0	2704	5.79	-3.5
8.0	2783	7.74	-3.25
10.0	2839	9.81	-1.9

Summary

Calibrating the Low-Level Gamma well with the SHP-270 Resulted in an Accurate and Precise Calibration

- Total Propagated Error =1.9% (1σ).
- Less Time Compared to The Radcal Model 1515 with the 1800 cc ion chamber
- Not Affected by Pressure and Temperature
- Zero Drift – Not a Problem